Dendritic Morphology and Storage Capacity in Hippocampal Pyramidal Neurons

Xundong Wu[1] and Bartlett W. Mel[1,2],
[1]Neuroscience Graduate Program and [2]Biomedical Engineering Department, USC

The hippocampus is involved in the storage of online, or episodic memories. The need to burn in new memories "at the speed of life" places a huge constraint on a neuromorphic learning system. In particular, the need to encode input patterns in a single presentation calls for high learning rates, but this also leads to rapid forgetting of remote memories. Assuming that CA1 pyramidal neurons must store a continuous stream of sparse input patterns arriving from CA3 via the Schaffer collaterals, and that the goal is to store these patterns as faithfully as possible for as long as possible, we have studied how the storage capacity of this pathway depends on (1) the CA1 dendritic morphology, that is, the number and size of the integrative subunits within the dendritic arbor (which we assume correspond to individual apical oblique branches in the stratum radiatum—see Losonczy & Magee 2006); (2) the local voltage thresholds needed to trigger synaptic learning and/or to trigger a local dendritic spike; (3) the synaptic learning step size; and (4) the number of long-term stable weight levels available to each synapse.

We modeled a system consisting of 25,600 sparsely activated afferents axons originating from CA3 cells, giving rise to a total of 2,560,000 modifiable synapses distributed across 400 model CA1 pyramidal neurons. We measured forgetting curves, that is, recognition error rate as a function of recency of learning. We report four main results under these conditions:

1. Storage capacity is maximized when branch learning thresholds are set very high, leading to extremely sparse branch activation in CA1. Thus, memory resources are best utilized when very few synapses are changed for each input pattern stored.

2. The most natural parameter that selects between optimal storage of recent vs. remote memories is the branch learning threshold. Lower thresholds mean more synapses are strengthened per input pattern, leading to better performance on recent memories; higher thresholds slow learning leading to better performance on remote memories.

3. Reflecting the extreme demands of episodic learning, storage capacity is maximized when synaptic weights are driven to their maximum values whenever selected for learning. High-resolution weights nonetheless benefit capacity, as synapses lacking training are gradually normalized back to their default values. We found capacity grows roughly linearly with bits per synaptic weight up through 4-5 bits.

4. The presence of even small amounts of spike noise in the input patterns drives the optimal branch size into the range of 200-500 synapses per branch. This is in the natural range for apical oblique branches of CA1 pyramidal cells (Megias et al 2001).

1. Losonczy, A. & Magee, JC. (2006) Neuron 50(2):291-307
2. Megias M, Emri Z, Freund TF & Gulyas AI. (2001) Neuroscience 102(3):527-40.